FINAL REPORT

HIGH SPEED SEMICONDUCTOR LASERS AND INTEGRATED RECEIVERS FOR MICROWAVE AND MILLIMETER WAVE SIGNAL TRANSMISSION

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Introduction

This project was proposed to be a three-year contract, but was cut off after one year (1987) of support. Sufficient progress was made to allow continuation for a year on minimal internal funds before proper support levels were received from a combination of ONR, RADC and IBM contracts at about the start of 1989. A major DARPA grant, expected to start August 1, 1990 will sharply expand this effort, to include several faculty members.

During the course of this project, two students did thesis research, one Ph.D. on lasers[1] and one M.S. on high speed photo detectors.[2] These theses were finished in September 1988, nine months after the contract was cut off. This report covers excerpts from those theses, as well as information obtained on other programs since that time.

High Speed Lasers

The initial effort concentrated on molecular beam epitaxial growth of Al,GaAs lasers on channeled substrates. This innovative concept, developed in conjunction with IBM in Zurich, allows the possibility of completely enclosing the active region of a single, narrow stripe laser during a single growth operation. As well as allowing small lasers for high speed modulation, it allows high efficiency, reliable devices without the necessity of a regrowth step. It allows thin quantum wells to be grown on the sides of the narrow ridge where the desired quantum well is to be located. This is caused by the longer diffusion length of Ga on some (m11) crystal planes, compared to that on (001) surfaces.[3] By widening the ridge at the location where mirror facets are to be formed by cleaving, the quantum wells are made thin there also. Because the thin quantum wells have band gaps up to .20 V higher in energy, they are not active during normal bias conditions, neither generating nor absorbing light. Thus the mirrors run cool, compared to the 400°C temperature of normal Al,GaAs lasers, contributing to reliability.

In order to obtain fast modulation rates, lasers must be made short. This reduces the photon life time. Single quantum well lasers have the lowest threshold currents when they are ≥ 200 μm long. By using multiple quantum wells, gain could be raised, and lasers with 4 quantum wells could be made with minimum threshold current for ~ 50 μm mirror separation and would yield two times as high a modulation frequency.

In later research, not funded by NASA, effort on In,GaAs/GaAs strained-layer and quadruple quantum wells have been successfully initiated and carried out. In these devices the light-mass holes dominate near the valence band, reducing the state density. This has allowed an increase of 50% in the laser modulation frequency for the same laser photon density and photon life time.[4] Experiments are now being planned and set up to have 50 μm laser cavities with quadruple strained-layer quantum wells, driven to $10^4 A/cm^2$ drive current density. These devices should be able to have 3 db bandwidths to 60 GHz.

The research at IBM in Zurich has recently succeeded in obtaining working strained-layer lasers on channeled substrates.[5]

High Speed Photodetectors for Use in Optical Receivers

This effort concentrated on interdigital electrodes of both the Schottky and ohmic variety. In the case of the ohmic contacts, gain is about five, but the response is slower. In the case of the Schottky contact, the speed is high, but the gain is about unity. The devices made on this project had interdigitated Schottky contacts, placed 1 μm apart, as shown in Figure 1. Both MESFET and $In_{.15}Ga_{.85}As/GaAs$ pseudomorphic MODFET wafers were used, and transistors were fabricated on the same wafer to show process compatibility for future photoreceivers.

After the devices were fabricated, the absorption spectra of the diodes, yielding current as a function of wavelength. The MESFET diodes started cutting off at 8600 Å as expected. The MODFET diodes showed ~ 2:1 less sensitivity except for a peak in sensitivity at ~ 8700 Å, which is the nominal location of the strained quantum well band gap. The absorption spectrum of the MODFET structure is shown in Figure 2.

In response to short optical pulses, when 10V bias was applied, the MESFET diodes had 6.8 - 8.04 ps system rise times when they were attached to 50 Ω transmission times. The fall times were longer, yielding half-height pulse widths of 17 ps. For the single quantum well (MODFET) structure, the rise time was only 1.8 ps, but

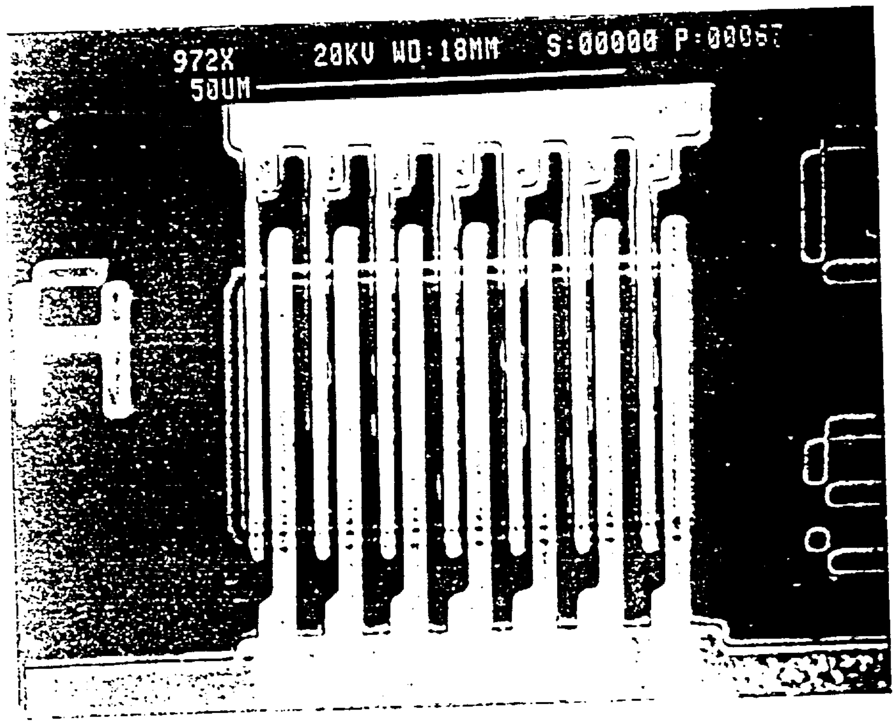

Figure 1. A close look at the fabricated photodiode with spacing ~ 1 μm.

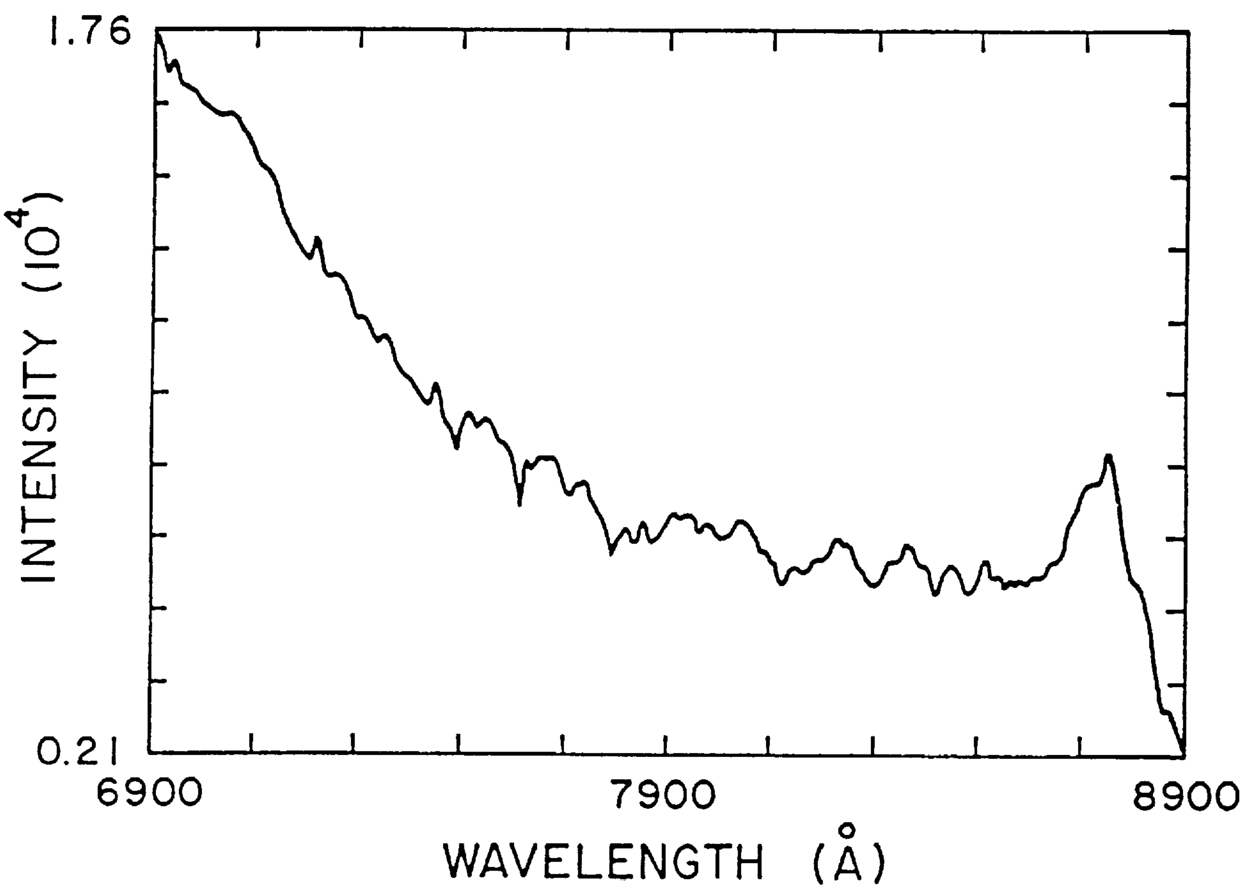

Figure 2. Absorption spectra of MODFET photodiode #12001.

the fall time is 25 ps, with a half-height pulse width of 20 ps. This inpulse photo-response is shown in Figure 3. It is proposed that much of the light, in both cases, penetrates into the buffer layer to the substrate interface. Any carriers generated deep inside have longer path lengths, and potential profiles to slow them down.

In later research at IBM in Zurich, Schottky fingers separated by .5 μm yielded 105 GHz frequency response.[6] Following this research, on a a program funded by RADC, Cornell designed and built a 60 GHz photoreceiver using such interdigitated Schottky fingers on a GaAs buffer layer. A $\lambda/2$ length coplanar waveguide was placed between the photodetector and the .25 μm-gate MODFET used to amplify the detected pulse. Rise times of about 4 ps were measured on this photo detector using ultra short light pulse techniques at the University of Michigan.

Conclusions and Recommendations

This project was a good start in the direction of obtaining the goal of 60 GHz photo transmitter and photo receiver. It was not funded at the level or for the time required for achieving the goal, but other programs continue at Cornell that can achieve these goals. It is recommended that short (~ 50 μm) cavity, pseudomorphic multiple quantum well lasers be integrated with short-gate (.15 μm/mushroom shape) post-detection amplifier stage(s). A resonant coplanar-waveguide, transmission-line transformer between the photodiode and the first amplifier stage is recommended to allow high sensitivity in such a high frequency, band-pass amplifier.

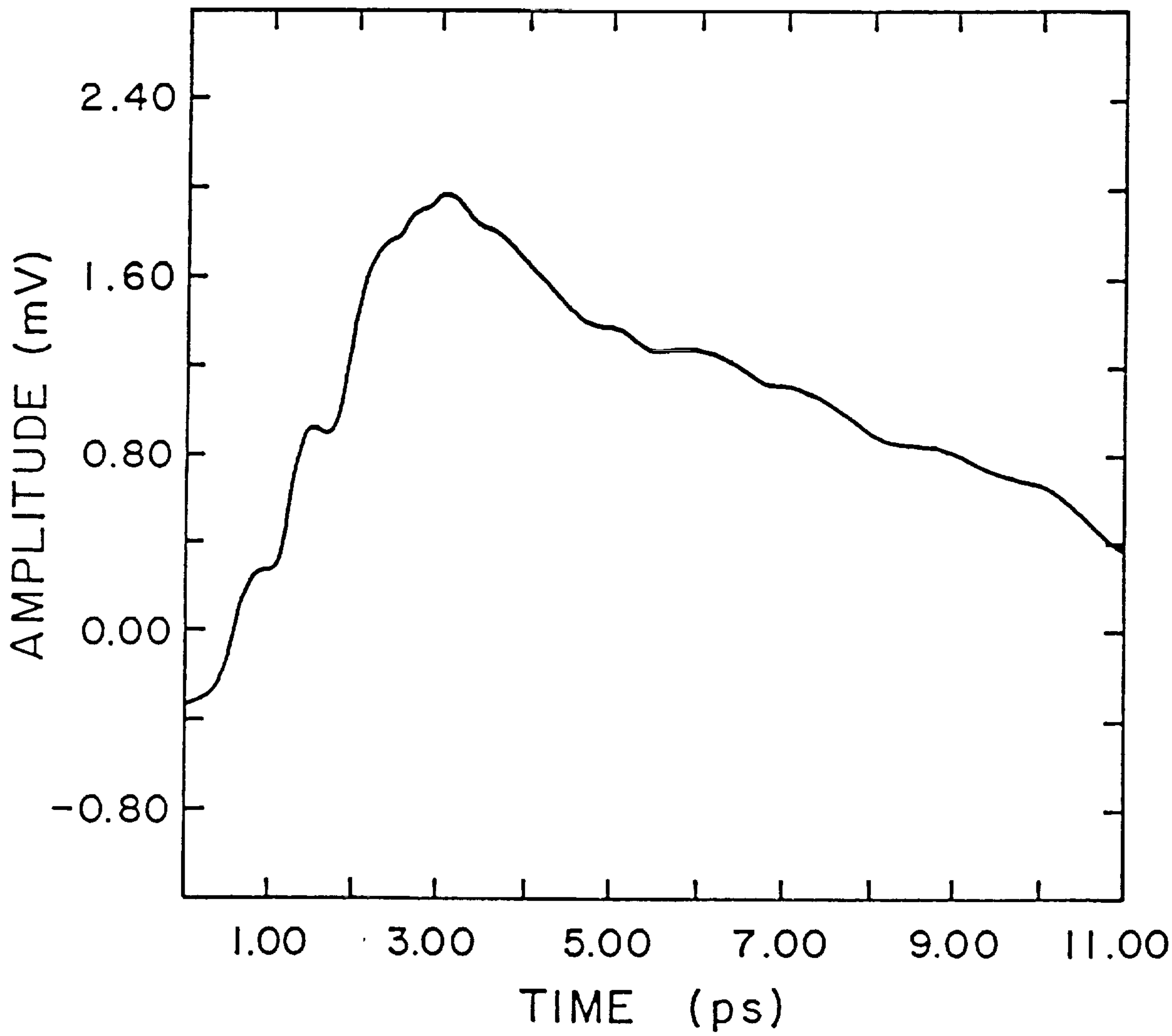

Figure 3. Impulse response of MODFET photodiode #12001.

References

1. "Molecular Beam Epitaxy of Aluminum Gallium Arsenide on Channeled Substrates", Edward Van Gieson, Ph.D. thesis, Cornell University, Jan. 1989.

Abstract

Molecular beam epitaxy of AlGaAs on channeled substrates has been investigated as a function of channel profile and growth conditions.

By optimizing the processing and growth parameters, it is possible to produce large variations in quantum well thicknesses and Al mole fraction of neighboring facets. A model has been developed which explains the observed growth behavior in terms of a surface flux of ad-atoms between the facets which increases the growth rate of favored planes at the expense of the source planes.

Relative growth rates can be controlled by varying the substrate temperature, channel width, and channel depth. Experimental results are presented for a variety of patterns, but with special emphasis on the pattern shape which produced the largest surface flux.

On the facets of a 4 µm wide ridge, Al mole fraction variations as large as $\Delta x = .16$ have been produced, corresponding to a nearly 200 meV difference in bandgap. Quantum well thicknesses on (100) sections of ridges can be varied from 72 Å to 97 Å by varying the ridge width from 30 µm to 4 µm, changing the width over which a nearly constant surface flux redistributes. The possibilities to increase the effects and achieve multi-dimensional bandgap engineering are discussed in relation to semiconductor laser applications.

2. "High Speed Photodetectors for Optical Interconnections", Benjamin Biing Chuyun Hao, M.S. Thesis, Cornell University, Jan.1989.

Abstract

This thesis reports on design, operation principles, measurement methods, and analysis of high speed photodetectors for the use of optoelectronic integrated circuits (OEIC),

especially in the area of high speed millimeter wave photoreceivers. In order to fabricate these high speed millimeter wave OEIC's, it is necessary to design and fabricate photodetectors with the widest bandwidth possible, reasonable quantum efficiency, and with a satisfactory noise property. Since the primary aim is to crease photodetectors with highest switching speed, not largest possible gain, only Schottky barrier photodiodes are measured though both photodiodes and photoconductors were fabricated and discussed.

All the photodetectors, both photodiodes and photoconductors, are planar and interdigitated. Therefore, they are very easy to be integrated into microwave or millimeter wave circuits with no modifications or additional steps necessary to the processing steps of MESFET or MODFET. The photodetectors have a photoactive area of 40 x 60 μm^2. This design is chosen for receiving light from a 50 μm diameter optical fiber. However, this is not necessary for general optical interconnection purposes.

The photodetectors' operation principles consist of two parts, photoconductivity and photodetection. Photoconductivity is related to material and epi-layers' properties, and its limits the ultimate response speed (intrinsic risetime and falltime) of photodetectors. Photodetection is related to detector design and parasitics of external circuits. It will affect the observed behaviors of the detectors. To understand the effects of photoconductivity on detector's response, picosecond bulk response, substrate effects, and femtosecond photoexcited hot carriers relaxation dynamics have to be considered. On the other hand, to understand photodetection better, detector design, fabrication, and external circuitry of the photodetector have to be paid more attention. Note that there is a big difference between photon absorption of MESFET layer structure (3 dimensional process) and of MODFET layer structure (2 dimensional process). By understanding photoconductivity better, it has been concluded that the intrinsic risetime of a photodetector should be around 1.3 ~ 2 ps.

The characteristics of the photodetector measured in this thesis are: DC characteristics, absorption spectra, and optical impulse response. Photovoltage and photocurrent are observed in

DC characteristics measurements. Nonlinear excitonic resonance behavior are seen in absorption spectra measurement. Finally, optical impulse responses of both MESFET and MODFET SQW detectors are measured using an electro-optic sampling technique, and the results give a risetime of 7 ps for the MESFET detector and 1.7 ps for the MODFET detector. The falltime of both detectors are comparable, 20 ~ 30 ps. The estimated bandwidth for the MESFET detector is over 22.5 GHz, and is over 40 GHz for the MODFET detector.

These results indicate the superior performances of these high speed photodetectors. They are clearly the best solution for future communication needs.

3. H. Meier, E. A. Van Gieson, A. Walter, Ch. Harder, M. Krahl and D. Bimberg, *Appl. Phys. Lett.* **54**, 433 (1989).

4. S.D. Offsey, W.J. Schaff, P.J. Tasker and L.F. Eastman, *IEEE Photonics Technology Letters*, **2** (1) 9-11 (Jan. 1990).

5. D.J. Arent, L. Brovelli, H. Jackel, E. Marday, and H.P. Meier, *Appl. Phys. Lett.* **56** (20) 1939-1941 (1990).

6. B.J. van Zeghbroeck, Ch. Harder, J.M. Halbout, H. Jackel, H. Meier, W. Patrick, P. Vettiger and P. Wolf, *Proc. 1987 IEDM.*